

HOW TO ESTIMATE INORGANIC FOULING FLUX ON RO MEMBRANE BY USING ROIFA-4?*

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ABSTRACT

The dehydration model provided a suitable chemical tool for prediction of inorganic fouling flux on the RO-membrane. Several important outputs had obtained from these research series that carried out by the present authors during the last five years. Among them, two indicative points are mastering the course, the first belongs to the nature of dissolving salt that are found as hydrated molecules and not as free ions. The second discovery is that the increasing of carbonates and sulfates minerals solubility with the increase of chloride ion (or probably NaCl) in its solution. By estimating the probable dissolving hardness-salt combination and their relative fouling fractions at a given Cl ion concentration it becomes easy to obtain the possible fouling load. Field correlation indicated the proposed guidelines for fouling potential limits. An excel spreadsheet had developed specifically for the RO inorganic fouling assessment (ROIFA-4), which is free for all and available upon request from the authors. The mathematical modeling has been described in detail, and a case study was also presented and discussed to illustrate the capability of this program. The ROIFA software subjected to many laboratory tests and field investigations for more than two years and found to be satisfactory.

Key Words: Inorganic Fouling, RO, Membrane, ROIFA, Dehydration Model.

INTRODUCTION

For many years the inorganic fouling potential for RO-membrane desalination has been predicted as what is applied in thermal desalination. Several models are in use, the first model had introduced by Langelier [1], since 1936, which based on the thermal behavior of water pH and hardness (as expressed empirically in CaCO₃), and the calcium carbonate fouling potential is determined on its saturation value at elevated temperature, which is known as Langelier Saturation Index "LSI". Later on, Ryznar [2] and Stiff-Davis [3] developed the earlier model to accommodate higher salinity effect. It should be noted that these "thermodynamic models" had basically established on the concept of "supersaturation" of dissolved salts in the heat

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exchangers at elevated temperature and sufficient contact time, and long time ago before the invention of RO-membrane.

On application of the above mentioned thermal indices for prediction of scale formation in reverse osmosis membrane separation many serious errors happened.

This is due to the basic difference between heat evaporation process and the membrane separation technology, which is a pressure driven process under normal temperature. Most of the recorded scaled RO-membranes were quite below the supersaturating level of their dissolved hardness chemical species.

During the past five years, the present authors involved deeply in RO hydrochemistry, this in order to investigate, study and try to solve the inorganic-scaling problems that associated with desalination of brackish and seawater by using the RO-membrane process. El-Manharawy and Hafez [4] presented a comprehensive study covering water chemical analyses, and XRF-mineralogy of deposited scales in more than 60 RO-plant cases. The obtained results indicated a strong relationship between the feed water chemical characteristics and the generated scale type, as well as its potential. It was clear that the molar ratio (SO_4/HCO_3) is gradually and positively correlated with the chloride molar concentration for most of the natural waters. This natural phenomenon shows that the variation in most of natural waters is so tight that ranges between 0 to ~20. For example, the molar ratio (SO_4/HCO_3) of: River Nile water is ~0.12, brackish groundwaters 1-5, salty waters 5-10, oceanic water ~12, and Red Sea water ~13. Some anomalous sulfate-enriched groundwater brines could be as higher than 30.

Furthermore, it was possible to conclude that there are two factors, i.e. water chemistry and permeate recovery, are controlling the inorganic scale formation on the RO-membrane, and scaling potential is directly proportional to the permeate recovery rate [5 and 6]. The present authors attributed the formation of inorganic scale to the dehydration of scale-forming species, which does not necessitate their concentration to be in the supersaturation zone.

In 2002, the present authors presented their “Dehydration Model [7]” providing reasonable explanation of the inorganic fouling mechanism happened during RO-membrane dewatering. This study revealed that the solubility of carbonate and sulfate minerals increases, in different ways, with the increase of chloride concentration. The model showed that not all hardness molecules are participating in fouling and scaling as it sought, but it follows selective preferential rules based on the associated chloride concentration in the RO brine solution. In other words, the available hardness species ready for fouling and scaling are lower than expected. The mathematical correlation between the theoretical and experimental fouling results proved that the proposed model is accurate and considered as a valuable tool for predicting inorganic fouling load.

The aim of this article is to present, illustrate and discuss the totally free “RO Inorganic Fouling Assessment – version 4 (**ROIFA-4**)” software that based on the mathematical model described in the earlier work of the “Dehydration Model, 2002” with some modification.

BASIC APPROACH

The RO Inorganic Fouling Assessment (**ROIFA-4**) is an excel spreadsheet specifically developed for calculation of the dehydrated hardness molecules flux on the surface of RO-membrane under pressure. It is based on the following findings:

- a) Minerals dissolve in water according to the hydration (or solvation) theory [8], where the dissociated ions/molecules attract water molecules according to their charge (z) to ionic radius (r). Low (z/r) ions (such as Na^{1+} and Cl^{1-}) are surrounding with single water shell of 4 to 6 water molecules. Intermediate (z/r) ratio ions (such as Fe^{3+} and Al^{3+}) tend to extract OH^{1-} from water to form insoluble complexes. Ions of higher (z/r) ratio can strongly extract O^{2-} from water and form their soluble oxy-anions such as the scale-forming ions (i.e. PO_4^{3-} , SO_4^{2-} , CO_3^{2-} , HCO_3^{1-} and SiO_3^{2-}). Due to their high (z/r) value, these hardness ions tend to attract more than one water shell around to form hydrated molecules. For example, the four oxygen bonded to sulfur, each of which carries an average charge of $-1/2$ ($2^- \div 4$ oxygen), this accept 3 water molecules around each oxygen in the first shell (a total of 12 H_2O) and less-attracted 6 in the second shell (a total of 24 H_2O), and so on. In low-salinity water, sulfate ion may accept up to 6 extra water shells, while in concentrated solution the attached water layers is normally lower than 4. Phosphate (PO_4^{3-}) has the same configuration of SO_4^{2-} ion but with higher residual charge ($-3/4$ each) therefore it attracts up to 8 shells. Both of SiO_3^{2-} and CO_3^{2-} ions have higher charges ($-2/3$ each), however, they are less branched. It also the same for dissolved cations (ex. Ca, Mg, Ba and Sr) where the positive charge is equally distributed around, and attracts the negative pole of dipolar water molecules.
- b) Under normal physical condition, i.e. without chemical interference, dissolving hydrated ions exist in solution as the original compound that dissolved from it (i.e. as ion-pairs hydrated molecules) and can re-crystallize again to its original mineral when subjected to water loss (i.e. dehydration). It is interested to mention that the hydrated molecules keep in “memory” the original crystal structure that dissolved from it.
- c) The dissolving hydrated ions are mostly present in less active ion-pairs associations, or “relaxed hydrated molecules”. The stability of these relaxed molecules in solution is increasing with the increase of water clusters around, consequently, under water loss condition the lower hydrated molecules will be less stable than the higher ones and tends to precipitate, i.e. the dissolved phosphate and sulfate molecules are most stabilized while carbonate and silica are less stabilized and tend to foul earlier.
- d) Dehydration of dissolving hydrated molecules probably done in a random way on the RO-membrane surface. The probability of “touching & dewatering” is directly proportional to the concentration of molecules in water mass that equally

distributed on membrane surface area per time. The magnitude of molecular dehydration is directly proportional to the applied pressure and defusing rate of pure water through a given membrane type.

- e) It is assumed that all dissolving hydrated molecules could be subjected to dehydration, and only a fraction of hardness molecules (ex. CaSO_4 and CaCO_3) will foul and exit the aqueous system as solid micro particles, while others (ex. NaCl , Na_2SO_4 and MgCl_2) will re-dissolve again, i.e. re-gain their water shells or part of it. This depends on their specific solubility and the available time necessary for re-dissolution. There are several evidences could support this assumption:
- e-1) Field observation indicated that the RO concentrated stream (brine) get turbid after short time from starting operation. Generally, turbidity increases 2-3 times during the first few hours from daily flushing and operation. In some recorded cases in the Red Sea RO-plants, the turbidity usually increases from less than 5 NTU to higher than 25 NTU in less than one hour.
 - e-2) The material chemical balance between the RO input and output is always disturbed, this because of the separation of some hardness species from the aqueous system as solid particulate, which can not determined by standard water analytical methods and may need strong acid digestion prior analysis.
 - e-3) The laboratory experiments on the closed recycling RO-setup indicated gradual continuous change in chemical composition of the circulating solution as recycling progress. The acid-leach of the micron filter-cartridge proved that considerable amount of hardness suspended solids retained and accumulate on the filter surface during closed circulation, and this must greatly considered when perform such experiments. These important field and laboratory observations support the idea of solid particulate formation due to reverse osmosis dehydration.
- f) Scale deposition is another issue; it depends on the maturation of fouled solid particle size to form the initial crystal nuclei under favorite condition, i.e. enough time and suitable place. The applied high mechanical pressure plays an important role in minimizing the time necessary for crystallization. It had found that massive carbonate and sulfate scales are usually located in the exit casing cavities and stretched counter flow at different magnitude. The flow pattern of water inside the RO membrane module is highly turbulent and well mixed; this is due to the insertion of complex mesh-spacer between membrane layers that delay the formation of hardness scale. Normally, water flows in ~1mm thickness layer between the spiral wound RO membrane.
- g) It had been observed that there is a considerable difference between the analytical molar ratio ($\text{CaSO}_4:\text{CaCO}_3$) found in brine solutions and that deposited in the formed scales, this phenomenon is common for all investigated cases but with different magnitude. This means that not all of the dissolved hardness molecules are readily to precipitate upon dehydration. This ratio called the fouling fraction (F_f).
- h) It had proved from our previous work that the solubility of carbonate and sulfate minerals increases widely as the chloride ion (or probably NaCl) concentration increases in solution [6]. The statistical data processing of analytical results that obtained from more than 60 RO feed, brine and scale samples indicated that there

is a systematic relationship between fouling fraction (F_f) of scales and the Cl mMole/kg of the brine.

CALCULATION OF THE PROBABLE DISSOLVING SALT COMBINATION

In order to obtain the inorganic fouling load (F_L , mM/kg), it is necessary to calculate the probable combination of dissolving hardness salts in brine solution, i.e. the concentration of: {Ca, Mg, Ba and SrCO_3 }, (Ca, Mg, Ba and $\text{Sr}(\text{HCO}_3)_2$), (Ca, Mg, Ba and SrSO_4), CaPO_4 , MgSiO_3 and Fe_2O_3 in mM/kg in the RO concentrated brine solution. These compounds usually constitute more than 99.99% of the RO inorganic scales, and its sum called the total fouling load (F_t , mM/kg).

We examined most of the available calculation models that currently used for predicting the “probable dissolving salt combination” and found that they are based on thermodynamics constants rather than pure chemistry. In fact, it is not possible to recalculate the individual original concentrations from these figures. Therefore, we preferred to consider the chemical stoichiometric calculation method that currently used in chemical laboratory, as the following simplified model:

- i) Convert feed-water ion concentration from (mg/l) to (mg/kg), multiplying by density, which could be estimated by using the following formula:

$$\text{Brine Density } (d_{\text{brine}}) = 0.000759 [\text{TDS}] + 996.977739 \quad (1)$$

- ii) Convert feed water (ion-mg/kg) to (ion-mM/kg), dividing by molecular weight.
- iii) Estimate brine-ion concentration, multiplying by the concentration factor (C_F):

$$C_F = 1 \div (1 - R) \quad (2)$$

where R is the recovery decimal (e.g. 0.3, 0.5, 0.7, ... etc.).

- iv) Distribute (CO_3^{2-} , mM/kg) with equivalent mMole of cations (Ca^{2+} , Mg^{2+} , Ba^{2+} , Sr^{2+} , Na^{+1} , K^{+1} and Fe^{3+}).
- v) Distribute (HCO_3^{1-} , mM/kg) with equivalent mMole of remaining cations (Ca^{2+} , Mg^{2+} , Ba^{2+} , Sr^{2+} , Na^{+1} , K^{+1} and Fe^{3+}).
- vi) Distribute (SO_4^{2-} , mM/kg) with equivalent mMole of remaining cations (Ca^{2+} , Mg^{2+} , Ba^{2+} , Sr^{2+} , Na^{+1} , K^{+1} and Fe^{3+}).
- vii) Distribute (Cl^{1-} , mM/kg) with equivalent mMole of remaining cations (Ca^{2+} , Mg^{2+} , Ba^{2+} , Sr^{2+} , Na^{+1} , K^{+1} and Fe^{3+}).

In case of water containing considerable amount of PO_4 and SiO_3 , combine the first with equivalent amount of calcium as $\text{Ca}_3(\text{PO}_4)_2$, and silicate with magnesium as MgSiO_3 . This step must do at the start and before any ionic distribution. The excess of Fe^{3+} could be expressed as Fe_2O_3 . This simplified ion-pair stoichiometric calculations showed that the accuracy of distribution of ions for probable dissolving salt combination is better than 98%.

CALCULATION OF FOULING FRACTION & FOULING LOAD:

The trend-line equations that concluded from the previous study of dehydration mode [7] used to predict the fouling fraction (F_f) of dissolved carbonate and sulfate of Ca^{2+} , Mg^{2+} , Ba^{2+} and Sr^{2+} those expected to foul at a given chloride concentration level:

i) Cl^{1-} range in brine: 0 – 10 mM/kg:

$$F_{f\text{-MCO}_3} = 0.0791 [\text{Cl}] + 0.2945 \quad (3)$$

$$F_{f\text{-MSO}_4} = 0.0645 [\text{Cl}] + 0.0470 \quad (4)$$

ii) Cl^{1-} range in brine: 10 – 200 mM/kg:

$$F_{f\text{-MCO}_3} = 0.0046 [\text{Cl}] + 0.9168 \quad (5)$$

$$F_{f\text{-MSO}_4} = 0.0013 [\text{Cl}] + 0.6126 \quad (6)$$

iii) Cl^{1-} range in brine: 200 – 800 mM/kg:

$$F_{f\text{-MCO}_3} = 0.00009 [\text{Cl}] + 0.0946 \quad (7)$$

$$F_{f\text{-MSO}_4} = 0.00019 [\text{Cl}] + 0.8407 \quad (8)$$

iii) Cl^{1-} range in brine: > 800 mM/kg:

$$F_{f\text{-MCO}_3} = 0.00 \quad (9)$$

$$F_{f\text{-MSO}_4} = 1.00 \quad (10)$$

Because of possible mathematical extrapolation, it should note that F_f value should be between zero and 1 (i.e. from 0% to 100% of foulant load), the results higher than 1 is to be considered as 1. In addition, there is no direct mathematical relationship between $F_{f\text{-MCO}_3}$ and $F_{f\text{-MSO}_4}$, this means that it is not necessary that summation of both is equal 1, they are independent from each other.

The corresponding individual fouling load (F_L) obtained from multiplying the compound analytical molar concentration (in mM/kg) by the estimated fouling fraction (F_f) at a given Cl concentration:

$$\text{Fouling Load } (F_{L\text{-MCO}_3}), \text{ mM/kg} = [\text{MCO}_3] \times F_{f\text{-MCO}_3} \quad (11)$$

$$\text{Fouling Load } (F_{L\text{-MSO}_4}), \text{ mM/kg} = [\text{MSO}_4] \times F_{f\text{-MSO}_4} \quad (12)$$

The total fouling load is the sum of the individual fouling flux of the investigated salts. For phosphates, silicates and excess iron oxide the fouling fraction has considered as 1, this because we couldn't detect any mathematical relationship between their concentration in brine and in deposited scale that usually contains over 50% of these foulants amount in many field investigations.

CALCULATION OF THE FOULING FLUX

The fouling flux (F_x) of individual foulant could be predicted from its concentration in brine that flows in a 1 mm thickness layer spreading over 1 cm^2 of membrane surface per time, which is normally around one second:

$$F_x, \text{ atom}/0.1\text{cm}^3 \cdot \text{sec} = F_L \times F_f \times 10^{-3} \times A_C \quad (13)$$

Where (F_x): number of hardness atoms found in 0.1 cm^3 per unit time (second), (F_L) is the fouling load, in $\text{mM}/0.1 \text{ cm}^3$, (F_f) is the fouling fraction, (A_C) is the Avogadro Constant [9] ($= 6.02214199 \times 10^{23}$).

HOW TO DEAL WITH ROIFA-4?

The mathematical model of **ROIFA-4** developed to carry over all the above-mentioned calculations automatically by means the windows excels capabilities. In the following some important instructions for use:

- 1) The **ROIFA-4** is an excel spreadsheet that composed of 4 sheets: “input”, “output”, “guidelines” and “calc”. Please copy under different name for use.
- 2) Start from the first “input” sheet and inter the basic information as well as the chemical ion analysis of feed water (in mg/l). The density correction will be done at once in “mg/kg of water.
- 3) Enter the permeate-recovery as a decimal (i.e. 0.0 or 0.3 or 0.35 or 0.42 and so on). You may enter any recovery value from 0.0 to 0.9.
- 4) Now you will get the “Chloride Content” -as mM/kg- in the concentrated brine automatically. If you prefer to set the recovery at 0.0 you will get the chloride content in the feed water.
- 5) Enter the obtained “Chloride Value” in the suitable Cl-range, in only one of the 4 Cl-ranges, and do not forget to enter “0” in the other 3 cells. Please note that this program based on the selective solubility of carbonates and sulfates compounds at different chloride levels, which compromises 13 basic equations as described earlier.
- 6) Turn on the second sheet “output” where you will find all you need to know. Compare the obtained “Fouling Flux”, “Silica Potential” and “Molar Ratio” with the given “Guidelines” in the third sheet. In addition, you will get the “Probable Dissolving Salt Combination (in mM/kg)”, the “Total Fouling Load (in mM/kg)”, the %wt/wt of different hardness-compounds, and the chemical composition of the resulted “Brine” at the given recovery.
- 7) The fourth sheet “Calc” contains all calculations, and it is hidden. You may unhide it, but it is advisable to un-touch any figure because this may destroy this calculation sheet.
- 8) The guidelines will lead you for the safe RO designing considering the fouling potential and its chemical type as well. For example, in table (1) when the obtained “Fouling Flux” is lower than $8.00\text{E}+17$ hardness molecules/ $0.1\text{cc}\cdot\text{sec}$. at recovery level 0.45 (=45%) your RO-system will run all right without need of any antiscalant. If the flux is higher you may lower the recovery level or use a suitable antiscalant that meets the chemical nature of fouling matters as described in table (2). The silica potential guideline is also given in table (3).
- 9) We may advise to draw a curve for the fouling flux vs recovery, this is simply done by assuming the recovery as: 0.0, 0.1, 0.2, 0.3, 0.35, 0.40, 0.45, 0.50, 0.55, 0.60, 0.65, 0.70, 0.75 and 0.80, but please do not forget to change the equation of the Cl-range when necessary. Due to mathematical extrapolation, the fouling

flux at the beginning of each chloride range may be lower than the last point in the preceding Cl-rang. In this case we find that the mean value of the highest, as calculated from the lower Cl-range, and the lower that calculated from the next Cl-range is reasonable.

NOTES ON ROIFA-4

- a) Field survey indicated that the high brackish waters [10] (i.e. lower than TDS=7000 mg/l) exhibiting poor linearity flux-recovery-curve, so the corresponding chloride ranges was modified under the name of **(ROIFA-4B)** and in the following order:
- A) Chloride range: 0 – 10 mM/kg,
 - B) Chloride range: 10 – 300 mM/kg,
 - C) Chloride range: 300 – 800 mM/kg, and
 - D) Chloride range: higher than 800 mM/kg.
- b) The investigated cases showed sign of starting inorganic fouling at flux ranges between $8.00E+17$ and $8.50E+17$ hardness-molecules/01cc.sec. This may attributed to the difference in membrane roughness as well as other operational conditions. Therefore, the guideline limit $8.00E+17$ was considered for safety.
- c) This program is sensitive for the accuracy of feed-water ion analysis. In the “output” sheet you will find the “Ion Difference %” between cations and anions, normally, this value is within 1% lower or higher. But if this value exceeding 1% up to 3% you may add some Na or Cl to bring down this value to be lower than 1%, the addition of Na or Cl will not affect the amount of hardness molecules. The negative sign means that anions are less than cations, while the positive difference means that cations are less than anions. If the ion difference is higher than 3% please search for another laboratory.
- d) The effect of variation in temperature is not covered in this program that based on normal temperature (25°C). However, in case of elevation of feed-water temperature the solubility of both calcite and gypsum is lowered considerably, and as a result the scaling potential will increase slightly. In case of lowering of water temperature to less than 25°C the solubility of calcite will increase therefore no problem is expected. For gypsum, its solubility is almost steady along the temperature range from 15 to 30°C, and then it goes down slightly towards 5°C. Therefore, under normal conditions (15 – 35°C) the obtained results will not change significantly.
- e) This program is useful for the controlled lowering of hardness molecules flux in feed-water to an acceptable level (i.e. $< 8.00E+17$ Molecules/0.1cc.sec.) economically, and don't need to remove all. For the carbonate-rich water this could be attained by acidification. For sulfate-rich water, as well as silicates and phosphates, either “Nano-Filtration” or “Alkalization” could be used. The alkalization method is described in detail in El-Manharawy and Hafez [11].

A CASE STUDY

In a classical case at south of Qusir on the Red Sea coast, a tourism foundation located drilled a shallow beach well (<10 meter) in a hard calcareous coral formation for feeding a 2000 m³/d SWRO desalination plant. The chemical analysis of this water (# GW-1, table-4a) indicated its lower salinity (16832 mg/l) and originated mainly from a wadi (valley) low-salty groundwater flows from the high lands at the west towards the Red Sea on the east. In spite of its lower salinity many previous field cases proved that such type of water -that comes in contact with the evaporite rocks- could exhibits strong carbonate and/or sulfate fouling potential. On applying the ROIFA-4 model on the water chemical composition it was found that the its fouling load is estimated as 1.348 mM/kg (table-4b) which is 3.34 times higher than that found in the Red Sea surface water (0.404 mM/kg at TDS=46859 mg/l).

The relative percentage of phosphates (18.87%), silicates (13.87%) and iron oxide (0.52%) are much higher than in the Red Sea surface water. The molar ratio (SO_4/Alk) of the investigated groundwater (table-4c) reaches 21.077 while it is only 13.402 for the Red Sea water, this strongly initiates sulfate fouling and scaling on the RO-membrane at higher recovery.

Supplying of the SWRO plant directly from the surface seawater –i.e. lower in hardness molecules- was avoided because of its shallow coral nature that is rich in aquatic fauna, flora and high TOC (=56 mg/l).

On the light of the obtained information it was recommended to continue drilling deeper, this in order to reach either clean filtered seawater or a mixing zone that may contain a lower level from hardness salts.

Table (4a) presents the chemical analysis of the other four collected samples (GW-2, 3, 4 and 5) at different depths (15, 20, 30 and 40 m) where salinity increases with depth (18073, 21007, 31256 and 43273 mg/l respectively). It was clear that the fouling load (table-4b) decreases with the increasing salinity by depth (GW1=1.347938, GW2=1.000983, GW3=0.956107, GW4=0.915627 and GW5=0.744499 mM/kg). By continuing drilling to about 50 m depth the groundwater chemical nature didn't changed significantly. It was realized that the last water type (i.e. GW-5) is the only choice as feeding water. This water type acquires almost half amount of starting hardness molecules, but still higher than the Red Sea hardness loads (0.403627 mM/kg).

In order to investigate the suitability of the studied water types for RO-membrane desalination, different scenarios were developed to estimate the inorganic fouling flux (hardness molecules/0.1cc.sec.) at different recovery levels (0, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75 and 80%) by using of ROIFA-4 program. Table-4d shows the obtained results while figure (1) illustrates the graphical relationships of the estimated inorganic fouling fluxes at different fresh water recoveries and indicating the following:

a) The inorganic fouling flux is independent from salinity. In other words, it is not necessarily that the higher salinity water has higher hardness molecules ready for

fouling as shown in the present case. It is clear that each water type acquire specific chemistry during its hydrologic cycle.

- b) The least salinity water (GW-1, TDS=16832 mg/l) attained the highest fouling flux value ($1.5161E+18$ Molecules/0.1cc.sec., table-4d) at recovery 40% which is almost twice the fouling guideline limit ($8.00E+17$ Molecules/0.1cc.sec.). At this range the inorganic fouling is very highly invited (table-1) even in the presence of a good quality antiscalant.
- c) The second higher salinity sample (GW-2, TDS=18073 mg/l) reached $1.0383E+18$ at recovery 40% that means it will subject to the risk of high inorganic fouling. A high quality antiscalant may help.
- d) The third higher salinity sample (GW-3, TDS=21007 mg/l) reached $9.8852E+17$ at recovery level 40% and will subject to the risk of medium fouling potential. A good quality antiscalant could overcome this limitation.
- e) The fourth higher salinity sample (GW-4, TDS=31256 mg/l) reached $9.2624E+17$ at recovery level 40% and will subject to medium fouling potential risk. A good quality antiscalant could overcome this limitation.
- f) The fifth higher salinity sample (GW-5, TDS=43273 mg/l) reached $7.4567E+17$ at recovery level 40% and could run safely in this range, or little bit higher, without the risk of inorganic fouling. Generally this case does not need any antiscalant.
- g) The coastal Red Sea surface water is widely variable in salinity and chemistry as well; it ranges from around 42000 mg/l at the north to higher than 47000 mg/l due south. It is affected with many factors, such as; flash flooding coming from nearby mountains, bathymetry, currents, climate, biota types, bio-diversity and intensive evaporation especially at shallower coral bottom. In the investigated location the Red Sea surface water could be desalinated –if possible- at safe recovery around 50%. This due to its molar ratio $[(Na+K)/(Ca+Mg)]$ reaches 9.166 (table-4c), which is relatively higher than that of seawater in other locations.
- h) It is possible to predict the expected scale chemical nature by means of the guidelines given in table-2 and table-3. For example, the expected fouling/scaling chemical nature of water type (GW-5) is mainly sulfate-type with lesser amounts of silicates and phosphates. The desired antiscalant(s) should full-fill these conditions.

In the present case it was decided to design the proposed SWRO desalination plant to operate normally at 38% recovery on the groundwater feed type GW-5. But after installation and startup it was possible to raise recovery to 42% without using any antiscalants, and no sign of inorganic fouling had appeared along one year of full operation.

CONCLUSION

The dehydration model provided -for the first time- a suitable chemical tool for prediction of inorganic fouling flux on the RO-membrane. Several important outputs had obtained from these research series that carried out by the present authors during the last five years. Among them, two indicative points are mastering the course, the first belongs the nature of dissolving salt that are found as hydrated molecules and not

as free ions. The second discovery is that the solubility of carbonates and sulfates minerals are increasing with the increase of chloride ion (or probably NaCl) in its solution. Simply, by estimating the probable dissolving hardness-salt combination and their relative fouling fractions at the given Cl ion concentration it becomes easy to obtain the possible fouling load. Field correlation indicates the proposed guidelines for fouling potential limits. An excel spreadsheet had developed specifically for the RO inorganic fouling assessment (**ROIFA-4**), which is free for all and available upon request. It had been subjected to many laboratory tests and field investigations for more than two years and found to be satisfactory. The economic importance of **ROIFA-4** lies in saving cost of total removal of hardness from feed water. The lowering of fouling flux to be around 8×10^{17} could consider satisfactory for either BWRO or SWRO desalination. When you may have unexpected results please contact the authors for discussion and/or modification when necessary.

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Table-1: Guidelines for Inorganic Fouling Flux on the RO-membrane surface.

Inorganic Fouling Flux Range (Molecules / 0.1cc.sec)		Fouling Potential Guidelines	Remarks
From	To		
0.00E+00	8.00E+17	No Fouling	No treatment is required
8.00E+17	9.00E+17	Low Fouling	Short flushing is essential
9.00E+17	1.00E+18	Medium Fouling	Antiscalant + Chemical Cleaning.
1.00E+18	1.50E+18	High Fouling	Antiscalant + Short Chemical Cleaning.
1.50E+18	2.00E+18	Very High Fouling	Antiscalant action is questionable.
>2.00E+18	-----	Excessive Fouling	Scale Blockage is a must

Table-2: Guidelines for Molar Ratio (SO₄/Alk) vs. Scaling Potential [10]

Water Type	Proposed Name	TDS Range* (mg/kg)	Chloride Range (mMol/kg)	Molar Ratio (SO ₄ /Alk**)	Carbonate Fouling Potential	Sulfate Fouling Potential
Type - 14	Brine Water	> 60000	> 800	> 15	Rare	Extremely High
Type - 13	Sub-Brine Water	50000 - 60000	700 - 800	12 - 15	Very Low	Very High
Type - 12	High Salty Seawater	40000 - 50000	600 - 700	11 - 14	Low	High
Type - 11	Sea Water	30000 - 40000	500 - 600	10 - 13	Medium	Medium
Type - 10	High Salty Water	15000 - 30000	200 - 500	9 - 11	High	Medium
Type - 09	Medium Salty Water	1000 - 15000	100 - 200	8 - 10	Very High	Medium
Type - 08	Low Salty Water	7000 - 10000	50 - 100	7 - 9	Very High	Medium
Type - 07	High Brackish Water	4000 - 7000	25 - 50	5 - 8	Very High	Medium
Type - 06	Medium Brackish Water	2000 - 4000	10 - 25	2.5 - 5	Very High	Low
Type - 05	Low Brackish Water	1500 - 2000	3 - 10	1.5 - 4	High	Low
Type - 04	High Fresh Water	1000 - 1500	1.5 - 3.0	1 - 3	High	Very Low
Type - 03	Medium Fresh Water	600 - 1000	1.0 - 1.5	0.5 - 1.5	High	Very Low
Type - 02	Low Fresh Water	300 - 600	0.5 - 1.0	0.25 - 1	Medium	Rare
Type - 01	Very Low Fresh Water	< 300	< 0.5	< 0.25	Low	Rare

*Total Dissolved Solids (TDS in mg/kg) is approximated for guidance purpose.

**Alk.: sum of alkalinity ions (= OH+CO₃+HCO₃, in mM/kg).

Table-3: Guidelines for Silicates Fouling on the RO-membrane Surface.

Silicate Fouling (%) of Total Fouling Load		Fouling Potential Guidelines	Remarks
From	To		
0.00	5.00	No Silicate Fouling	No treatment is required
5.00	10.00	Low Silicate Fouling	Short flushing is essential
10.00	20.00	Medium Silicate Fouling	Antiscalant + Chemical Cleaning.
20.00	30.00	High Silicate Fouling	Antisc. + Short Chemical Cleaning.
30.00	50.00	Very High Silicate Fouling	Antiscalant action is questionable.
> 50	-----	Excessive Silicate Fouling	Scale Blockage is a must

Table-4a: Chemical analysis of five beach-wells groundwater, south of Qusir, and the Red Sea surface water in this location.

Ion, mg/l	GW-1	GW-2	GW-3	GW-4	GW-5	Red Sea
Na ¹⁺	3732	4621	5645	9204	13664	15037
K ¹⁺	65	71	75	221	331	401
Ca ²⁺	1468	1283	1322	972	722	451
Mg ²⁺	614	504	552	1008	1296	1488
Ba ²⁺	0.74	2.67	2.84	1.58	0.97	0.01
Sr ²⁺	2.25	0.39	0.83	6.73	8.96	9.82
Cl ¹⁻	8123	9079	10797	16879	24179	26576
HCO ₃ ¹⁻	82	67	65	78	94	131
CO ₃ ²⁻	0.00	0.00	0.00	0.00	0.00	0.00
OH ¹⁻	0.00	0.00	0.00	0.00	0.00	0.00
SO ₄ ²⁻	2721	2418	2521	2861	2957	2764
SiO ₃ ²⁻	14.09	22.11	22.02	15.01	12.83	0.55
Fe ³⁺	0.47	0.28	0.26	0.94	0.13	0.03
Mn ⁴⁺	0.00	0.00	0.00	0.28	0.00	0.00
PO ₄ ³⁻	9.57	4.08	4.22	8.22	6.61	0.89
TDS, mg/l	16832	18073	21007	31256	43273	46859

Table-4b: Total hardness fouling load of the investigated waters and their relative percentages as obtained by ROIFA-4 software.

	GW-1	GW-2	GW-3	GW-4	GW-5	Red Sea
Total Fouling Load, mM/kg	1.347938	1.000983	0.956107	0.915627	0.744499	0.403627
Carbonates (%)	12.167	10.103	9.154	8.766	9.962	23.894
Sulfates (%)	54.569	49.278	47.988	43.456	42.354	68.139
Silicates (%)	13.873	29.342	30.662	21.992	23.325	1.849
Phosphate (%)	18.871	10.844	11.769	24.121	24.068	5.993
Iron Oxide (%)	0.519	0.434	0.428	1.665	0.291	0.125

Table-4c: Molar ratio indicators of the investigated waters as obtained by ROIFA-4 software

Molar – Ratio	GW-1	GW-2	GW-3	GW-4	GW-5	Red Sea
(SO ₄ / Alk*)	21.077	22.923	24.635	23.298	19.981	13.402
(SO ₄ / Cl)	0.124	0.098	0.086	0.063	0.045	0.038
(Alk* / Cl)	0.006	0.004	0.004	0.003	0.002	0.003
(Na / Cl)	0.709	0.785	0.806	0.841	0.872	0.873
(K / Cl)	0.007	0.007	0.006	0.012	0.012	0.014
(Ca / Cl)	0.160	0.125	0.108	0.051	0.026	0.015
(Mg / Cl)	0.110	0.081	0.075	0.087	0.078	0.082
(Na+K) / (Ca+Mg)	2.650	3.845	4.443	6.177	8.450	9.166
(SO ₄ / SiO ₃)	152.950	86.616	90.675	150.963	182.540	3980.230
(HCO ₃ / SiO ₃)	7.257	3.779	3.681	6.480	9.136	296.995
(Ca / SiO ₃)	197.788	110.160	113.972	122.934	106.831	1556.680
(SiO ₃ /Cl)*1000	0.808	1.135	0.950	0.414	0.247	0.010
Cl/SiO ₃	1237.222	881.235	1052.272	2413.283	4044.399	103697.726
Mg/SiO ₃	136.412	71.357	78.473	210.221	316.209	8469.080
(Ca / PO ₄)	363.497	745.166	742.345	280.209	258.835	1200.807

*Alk.: sum of alkalinity ions (= OH+CO₃+HCO₃, in mM/kg).

Table-4d: Inorganic Fouling Flux (Molecules/0.1cc.sec) of the investigated waters at different freshwater recoveries as obtained by ROIFA-4 software

Recovery (%)	GW-1	GW-2	GW-3	GW-4	GW-5	Red Sea
0	8.7307E+17	5.9565E+17	5.6273E+17	5.1474E+17	4.2980E+17	3.6475E+17
30	1.2807E+18	8.7590E+17	8.3164E+17	7.7383E+17	6.3440E+17	5.3037E+17
35	1.3885E+18	9.5025E+17	9.0337E+17	8.4419E+17	6.8556E+17	5.7330E+17
40	1.5161E+18	1.0383E+18	9.8852E+17	9.2624E+17	7.4567E+17	6.2376E+17
45	1.6692E+18	1.1442E+18	1.0912E+18	1.0140E+18	8.1731E+17	6.8394E+17
50	1.8566E+18	1.2739E+18	1.2174E+18	1.1200E+18	9.0412E+17	7.5691E+17
55	2.0908E+18	1.4363E+18	1.3760E+18	1.2507E+18	1.0115E+18	8.4724E+17
60	2.3918E+18	1.6456E+18	1.5813E+18	1.4159E+18	1.1476E+18	9.6189E+17
65	2.7925E+18	1.9250E+18	1.8246E+18	1.6311E+18	1.3258E+18	1.1122E+18
70	3.3511E+18	2.2818E+18	2.1442E+18	1.9231E+18	1.5689E+18	1.3175E+18
75	4.0643E+18	2.7621E+18	2.5991E+18	2.3417E+18	1.9200E+18	1.6146E+18
80	5.1423E+18	3.4977E+18	3.2976E+18	2.9907E+18	2.4698E+18	2.0813E+18

